Chapter 1:   INTRODUCTION

1.1   Tsunami waves

This is a study of the generation, propagation, and runup of waves over three dimensional physical bathymetry. Tsunamis—sometimes referred to as tidal waves—are sea-surface gravity waves generated by large-scale underwater disturbances. Typical trigger mechanisms are earthquake-initiated sea-bed displacements, volcanic eruptions, landslides (including underwater landslides), impact of large objects (such as meteors) into the open ocean and underwater explosions. Such impulsive disturbances create water-wave motions where the entire water column—from the bottom to the free surface—is set in motion. The surface waves generated by such motions typically have a very long wavelength compared with the depth of the ocean basin where they propagate; they are commonly referred to as long waves and they are usually modeled mathematically using a depth-averaged approximation of the Navier-Stokes equations referred to as shallow-water wave theory.

Two of the most devastating tsunami catastrophes in history are associated with the eruption of the Theva volcano, Greece around 1500 BC and of the Krakatau volcano near Java in 1883. The well-documented Krakatau eruption generated a tsunami wave which killed 36,000 people and set the entire surface of the ocean in long wave motion for days. The exact generation mechanism of this tsunami is still unclear, but there is speculation that the impact of the falling debris from the explosion (Yokoyama, 1981), the underwater vapor explosion (Simkin and Fiske, 1983) and caldera formation (Kawamato et al., 1993)

caused the tsunami. Landslides triggered by earthquakes often cause localized but very intense tsunami waves. The highest ever-recorded runup of surface waves was produced by the landslide-generated wave in Lituya Bay, Alaska on July 10, 1958 (Miller, 1960). The earthquake triggered a rockslide which generated a huge wave propagating along the narrow bay climbing more than 530 meters (1,720 feet) up the opposite shore of the Bay. The runup along the rest of the bay shore varied from 30 to 200 meters.

Earthquakes are the leading cause of tidal-wave generation. Only since 1992, eighteen earthquakes generated tsunamis which claimed 2000 lives and caused damage in many coastlines around the Pacific rim. The largest of these events are listed in Table 1.A powerful earthquake occurring under the ocean floor can generate a tsunami wave by the deformation created on the sea floor. This sea-bed displacement translates into the deformation of the free-water surface, creating long surface gravity waves which radiate from the source area. These waves—unlike ordinary seismic waves—can transfer considerable amount of the earthquake's energy to shorelines located very far from the earthquake source region. A tsunami generated by the earthquake in Chile in 1960 crossed the Pacific ocean in 22 hours and struck the Japanese coastline. The most destructive tsunami to hit the Hawaiian Islands was generated by an earthquake that occurred 3500 kilometers away, near the Aleutian Islands in 1946. However, such farfield tsunamis, i.e. tsunamis which affect distant (more than 100km) coastlines, are now known to be less frequent than believed earlier. Ninety percent of the damage due to tsunami attack occurs along shorelines distant less then $300km$ from the source of the tsunami, these tsunamis are referred to as nearfield. Most tsunamigenic earthquakes occur on subduction zones, which are stretched along highly populated

and well developed coasts around the Pacific rim, i.e. most potential tsunami sources are always dangerously close to coastal communities.

Table 1 SUMMARY OF 1992-1996 TSUNAMIS

Location	Year	Date	Time	Depth	M_s	max Runup	Casualties
Cape Mendocino	1992	Apr 25	18:06	15	7.1	1	0
Santa Cruz Island	1992	May 27	5:13	19	7.0	small	0
Sanriku	1992	July 18	8:36	29	6.9	0.5	0
Nicaragua	1992	Sept 2	0:16	45	7.2	10	170
Flores Island	1992	Dec 12	5:29	28	7.5	26	more than 1000
Kamchatka	1993	Jun 8	13:03	71	7.3	0.1	0
Hokkaido	1993	Jul 12	13:17	17	7.6	30	200
Guam	1993	Aug 8	8:34	59	8.0	1	0
East Java	1994	Jun 2	18:17	18	7.2	14	220
Cape Mendocino	1994	Sep 1	15:10	10	7.0	0.1	0
Kurils (Shikotan)	1994	Oct 2	13:22	33	8.2[a]	10	0
Kurils aftershock	1994	Oct 9	7:55	23	7.0	0.2	0
Mindoro Island	1994	Nov 11	19:15	33	7.1	7	70
Sanriku, Japan	1994	Dec 28	12:19	33	7.5	1	0
Jalisco, Mexico	1995	Oct 9	11:00	30	7.9[a]	11	1
Palu, Indonesia	1996	Jan 1	16:05	39	7.8	4	24
Biak, Indonesia	1996	Feb 17	15:00	*	8.2	8+	53
Peru	1996	Feb 21	12:51	15	7.5[a]	5	12

a. the magnitude is M_w

1.2 Numerical modeling

The problem of tsunami modeling is arguably the most important part of tsunami-hazard mitigation efforts. The potential of numerical models to reproduce tsunami evolution over physical bathymetry and to calculate runup and penetration on coastlines on the coasts with complicated topographies can be utilized in tsunami hazard reduction programs in two ways:

- for real-time monitoring of the tsunami evolution and prediction of coastal effects,
- for inundation calculations of historic or hypothetical events to assist civil defence in drawing evacuation plans.

Real-time tsunami warnings are the mission of tsunami warning centers. At present, none of the tsunami warning centers around the Pacific use any real-time numerical models of tsunami evolution during emergency procedures. The tsunami warnings are issued based on historic records and on available seismic information from the seismographic networks such as epicenter location and magnitude estimation of the earthquake and sometimes on free-surface amplitudes recorded by tidal-gage network or by eyewitness accounts. The arrival time of the wave at different locations is the only information issued by the centers, and no estimation of the wave amplitudes are made. This difficulty of even to first-order estimating the tsunami-wave amplitude can cause costly false alarms. For example, an evacuation of the coastal areas of the Hawaiian Islands after the October 2, 1994 Kuril tsunami resulted from such a false alarm and it cost the State of Hawaii $30 million. When these tsunami waves reached the island, the amplitude was only about fifty centimeters—

hardly noticeable over background wind waves without tidal-gage records. Clearly, implementation of the numerical modeling of wave evolution into the tsunami warning can make the warning more effective.

Another problem is the very short time-frame available for the calculations during the emergency. The growth of computer processing speed during recent years allows the calculation of the tsunami propagation and even inundation computations in a matter of minutes. Therefore, numerical modeling can conceivably make predicted inundation information available during the emergency procedures. However, the slow estimation of the earthquake source parameters by seismologists is still an obstacle, since this is the basic input information for the tsunami models. Recent studies (Schindele et al., 1995) have raised the possibility of the real-time estimation of earthquake parameters as well as prediction of the tsunami potential of the earthquake.

The other use of the tsunami evolution calculations is the estimation of the potential flooding of tsunamis along a seismicly active coastlines for developing civil defence procedures both for zoning and for drawing evacuation plans. The numerical models can be used to either simulate relevant historic events or a hypothetical event identified using geologic, sedimentologic and seismic evidences. Calculation of the inundation areas would provide the necessary information for creating evacuation plans for the specified areas. The models can also estimate flow velocities during the tsunami attack, velocities relate to the dynamic force of the wave imposed on structures. This information can be used for improving the design codes for coastal structures. The other important information calculated by

inundation models is the level of the water withdrawal during the attack—crucial information for port facilities, since the water can withdraw as low as 10 meters below current water level during a tsunami attack.

1.3 Tsunami wave evolution

The evolution of earthquake-generated tsunami waves has three distinctive stages: generation, propagation, and runup.

The generation stage of the tsunami evolution includes the formation of the initial disturbance of the ocean surface due to the earthquake-triggered deformation of the seafloor. This initial water-surface disturbance evolves into a long gravity wave radiating from the earthquake source. The modeling of the initial stage of the tsunami generation is closely linked to studies of the earthquake source mechanism. Since this study uses a generation model as initial conditions for the simulation of historic tsunamis, the generation model is briefly discussed in the beginning of chapter 4. The hydrodynamic part of the tsunami generation process is usually studied with linear models since the formation of the gravity wave from the initial water disturbance is a fairly slow process which is driven mostly by hydrostatic forces. The non-linear effects are negligible.

The propagation of the tsunami wave from its source toward the inundation areas is the part of the wave evolution where dispersion may be important. This effect changes the wave shape due to the slightly different propagation speed of waves with different frequencies. The dispersive effects become pronounced if the wave propagates over a distance of

three or more wavelengths, as in trans-oceanic tsunami propagation. Such cases are studied with dispersive models such as the Boussinesq model. The near-field tsunamis are not affected much by dispersion because their propagation distances are often less than one wavelength. Since this study is targeted mostly at near-field events that create the most severe inundation in nearby coastlines, dispersive terms are not included in the field model. The dispersion can be taken into account even without the use of the dispersive terms in the governing equations. Shuto (1991) suggested that the numerical dispersion of finite-difference algorithms could be used to simulate the dispersive effects of the wave propagation. This method allows the use of non-dispersive linear or of non-linear equations for the wave propagation modeling, and still account for the dispersive effects.

The runup is probably the most underdeveloped part of past tsunami modeling efforts. Up until recently, there was a lack of high-quality experimental and field data regarding the long wave runup process to test the performance of models, especially for effectively three-dimensional cases. This obstacle has been overcome after a series of large-scale runup experiments was conducted at CERC (Briggs, Synolakis, Green, Harkins, 1995) and after several post-tsunami field surveys which provided high quality field data (Satake et al, 1993, Yeh at al, 1993, Synolakis et al 1995, Imamura et al, 1995, Yeh et al 1995, Borrero et al, 1997).

It has been common practice to estimate tsunami runup heights by modeling wave propagation up to the $10m$ contour and then use the wave height at that depth to infer the maximum runup. These models are referred to as inundation models. The tsunami inunda-

tion maps for most of Hawaii have been developed using this simplified technique. The field surveys of the 1992–1996 tsunamis showed that these models produced predictions differing by a factor ranging from three to ten compared with field observations, raising concern because of their ubiquitous use in civil defence planning and fueling controversy as to whether the poor predictions were due to inadequacy of the shallow-water approximation, now used by most hydrodynamic inundation models. The new data from the laboratory experiments and from the field suggest that the evolution of the wave during this last stage of propagation is substantial and the wave height can change significantly from $10m$ depth to the coastline. Besides, the runup height itself might not be the indicator of the severity of the wave impact. The magnitude of the currents during the wave runup determine the scale of coastal destruction due to tsunami attack. Since the inundation flow is non-linear, the flow velocities do not necessarily correlate with the height of the wave. In fact, some preliminary evidence suggested that during overland flow the maximum flow velocities occur when the flow depth is minimum. This flow velocity estimation component of the tsunami evolution is completely missing from "inundation" modeling without runup computations.

Tsunami waves are long waves (small depth-over-length ratio) during their entire propagation and even during the runup phase, making the long-wave approximation an attractive and popular method for modeling tsunami generation and propagation. However, the runup process often involves wave breaking, supercritical currents, overland flows, all complicating the modeling of the process, not to mention that the complexity of the flow near the tip of the climbing or receding wave has raised questions about the applicability of

the depth-average approximation for the runup modeling. In this dissertation the long wave approximation for modeling the complicated inundation flows will be evaluated as well the applicability of the approximation for the inundation studies. Although the model describes all stages of tsunami wave evolution, the main focus of the work is determining the wave transformation during the runup of surface water waves on the beach with arbitrary profile, the process when the wave tip is climbing up the dry beach and consequently withdraw. The problem arises not only in tsunami studies but in many engineering application whenever the coastal effects of wave action is estimated.

1.4   Long-wave inundation models

The model uses long wave approximation, which assumes that the ratio of depth over the wavelength is small. Long-wave processes such as tides and even near-shore wind waves (B. Raubenheimer, et al., 1995) have also been modeled successfully using the shallow water wave equations and they can be considered as possible applications of the model.

Tsunami inundation studies can be grouped into two-dimensional models and three-dimensional models. To avoid confusion, we will refer to a model describing physical phenomena with one horizontal dimension and one vertical dimension as a "1+1" model regardless of its mathematical interpretation. Similarly, a phenomena with two horizontal and one vertical dimensions will be referred to as "2+1" model.

A few different approaches have been used for the runup studies of both 2-D and 3-D long-wave inundation problem. Many of these models were presented at the International

Workshop on Long Wave Runup in Friday Harbor, Washington on September 12-17, 1995, sponsored by the National Science Foundation. All participating modelers—most of them based on the long-wave approximation—computed solutions for the certain benchmark problems, provided by three organizers. These four benchmark problems were

1) a wave packet propagation along a sloping beach,
2) the interaction of incident solitary wave with a conical island,
3) the runup of solitary waves on a vertical wall, and
4) tsunami runup around Okushiri Island during the 1993 Hokkaido tsunami.

The majority of numerical models for the three-dimensional tsunami inundation use the long-wave approximation. The linear shallow-water equations can provide analytical results for the runup height of plane waves for simple and complicated 1-D beach profiles (Synolakis, 1986, 1987; Tadepalli and Synolakis, 1994,1996; Kanoglu, 1997) and even for 2-D piecewise-linear beaches (Kanoglu 1997). Nevertheless, to model the flow evolution on the dry bed (depth below zero) with complicated 2-D topography where the waves experience breaking and overflow, non-linear equations are essential for modeling. Most long-wave inundation models utilize classic non-linear shallow-water-wave equations (NSW) which may include bottom friction terms and/or viscosity terms. The major difference between the models is the method of numerical solution of the equations. A review of existing models of the three-dimensional long wave runup is given in Chapter 3.

Several studies have applied different mathematical models for the long wave inundation modeling. Grilli and Svensen (1989) utilized a fully nonlinear potential flow theory to model long wave runup in a two-dimensional domain without vertical integration, i.e.

without assuming vertical uniformity of the flow, an essential postulate for the long wave theories. This model is capable of computing the detailed behavior of the highly nonlinear waves and the vertical velocity distribution of the flow up to the point of breaking without assumptions about the amplitude or the wavelength. It only assumes inviscid potential flow. Comparison of the results with long wave theories shows that, although the potential theory reproduces details of the breaking wave front—unrealizable by the long-wave approximation—the overall wave behavior, such as amplitudes and runup height are reproduced by long-wave models virtually likewise. The drawback of the potential flow approach is the immense computational cost and inability of the model to estimate the runup of breaking waves. A three-dimensional version of the model has not been reported up to date.

Three or two-dimensional models using the Navier-Stokes equations for the free-surface problems (see, for example Raad, 1995) are usually not applied to long-wave runup problems. The Navier-Stokes equations are the most general flow description known. To resolve all the eddies appearing especially during wave breaking, numerical models must have very fine resolution in all coordinate directions, making them computationally very expensive even for two-dimensional simulations; they are used mostly for detailed studies focusing on the details of the wave breaking and wave interaction with obstacles at small scale—not for the large scale propagation and runup modeling. Any extension of the 2-D Navier-Stokes model to the three-dimensional runup modeling would need much larger computing resources and might be considered only for very specific studies of the wave-structure interaction, not for the whole generation-propagation-runup cycle. Mader (1986)

presented a Navier-Stokes based numerical model for tsunami propagation, but it did not include runup computation.

Fujima (1995) reported a runup model based on the Euler equations. The model was used to solve the 3-D benchmark problem of runup on conical island. The model uses the Markers-And-Cells (MAC) method to solve the equations, and it does not take into account viscous or bottom friction forces; also it cannot compute overturning waves or breaking. The boundary conditions used on the moving wave tip suggest hydrostatic pressure distribution locally, making the runup model somewhat similar to those using shallow-water approximation. Since viscous and overturning effects were not included in this model, the results of the computations qualitatively and quantitatively did not differ substantially from the shallow-water model's results, which compared well with the laboratory data.

The problem of determining the 2+1 evolution (propagation over one-dimensional topography) and runup of long waves on a sloping beach is a classic problem in hydrodynamics. Analytical solutions for the runup of non-breaking sinusoidal, cnoidal and solitary waves exist, and recently there have been reports of numerical solutions for breaking periodic and solitary waves. The understanding of the solution of this two-dimensional problem is believed to be of importance for solving the three-dimensional runup problem, i.e., two propagation dimensions (Liu et al. 1991). In the present study, the 1+1 model serves as a testing and development tool for the 2+1 model which is based on the same finite-difference scheme as the 1+1. That model hereafter referred to as VTCS-3 is a splitting method that separates the 2+1 problem into two 1+1 problems. It utilizes the shoreline algorithm of

the 1+1 model and uses the same finite difference scheme. Despite the limitations of the field equations, it is believed—and it will be attempted to demonstrate in this study—it simulates most of the important tsunami wave characteristics during the three-dimensional long-wave runup well enough to use the results for the engineering applications. We demonstrate the ability of the model to reproduce the laboratory data of three-dimensional runup very well and to simulate various features of the historic tsunamis.

Chapter 2 describes the 1+1 model, now known as VTCS-2 (Titov and Synolakis, 1995). Chapter 3 describes VTCS--3 and its validation through comparisons with large scale laboratory experiments. Then, VTCS-3 is used to model five of the 1992-1996 events. The predictions are described in chapter 4 where they are compared with runup measurements from field surveys; in the same chapter the effects of the grid resolution for field predictions is explored. Chapter 5 summarizes the conclusions. The basic contribution of this thesis is the development of a robust 2+1 shoreline algorithm which can even model the runup of mildly breaking waves without any fudge factors. What has been shown is that the splitting method for solving the 2+1 shallow-water wave equations is adequate for making very realistic predictions for the tsunami runup, assuming that inundation computations are performed. Without inundation computations, i.e. when the propagation calculations is interrupted at some threshold offshore depth, the predictions can greatly underestimate the runup. Also, the results are suggestive that the effects of bathymetric and topographic grid resolutions are   important to first order.